EXPANSION ISENTROPES OF THE EXPLOSION PRODUCTS OF CONDENSED EXPLOSIVES

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The expansion isentropes of the explosion products of two TNT/RDX compositions (50/50 and 25/75) have been investigated. Attention is concentrated on the little-studied region of pressures below 100 kbars. Data on the expansion isentropes were obtained by measuring the shock wave parameters in various media (aluminum, plexiglas, polystyrene foam, argon, air). Points were obtained on the shock Hugoniots of argon precompressed to 10, 15, and 50 atm. An equation of state of the explosion products that satisfactorily describes the experimental material obtained is formulated.

1. The behavior of the isentropes of expanding explosion products is quite well known for various explosives in the range of pressures close to the corresponding Jouguet pressures thanks to the condition of tangency of the isentropes to the detonation rays [1]. The nature of these relationships is also clear at relatively small pressures, in the region of which the explosion products may be regarded as a perfect gas. However, the intermediate region (1 kbar $\geqslant p < 100$ kbars) has received relatively little attention.

Jones and Miller [2] calculated the isentrope up to large expansion ratios for the explosion products of TNT. For this purpose they used the experimental dependence of the detonation velocity (D) on the initial density of the explosive (ρ_0) and made certain simplifying assumptions.

Certain experimental data on the isentropic expansion of the explosion products of TNT/RDX 50/50 at relatively high pressures are presented in [3, 4]. Deal [5] obtained experimental points on the isentrope of the detonation products of composition B. Measurements of the shock wave velocities in targets of varying rigidity enabled him to trace the isentropic expansion curve of the explosion products over a broad pressure range. At pressures below 100 kbars the isentrope of the explosion products was determined at 40 kbars by unloading the explosion products into porous polyurethane and allowing them to expand into argon and air under normal conditions ($p \approx 0.9$ and 0.6 kbar).

We have made a thorough investigation of two explosives—TNT/RDX 50/50 and TNT/RDX 25/75—chiefly in the pressure region below 100 kbars. As the materials into which the explosion products expanded we used porous polystyrene with variable initial density and argon precompressed to pressures of 100 atm and below, as well as air at normal pressure.

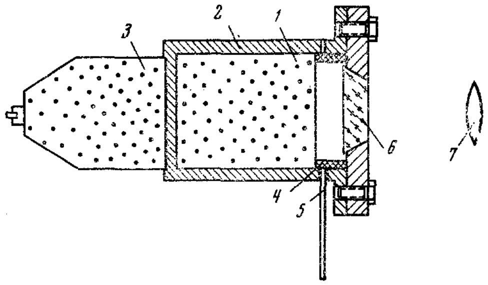

Fig. 1

2. The isentropes of the explosion products were investigated by the "target" method described in detail in [3]. In this method the parameters of the shock wave in an inert material (target) in direct contact with the investigated explosive are measured. Measurements of the wave or particle velocity in a target with known dynamic properties make it possible to determine a point on the expansion (or loading) curve of the explosion products. In all the experiments plane detonation waves were created in the investigated charges by means of special lenses [3]. The charges were cylinders 120 mm in diameter and 180 mm long. We investigated two TNT/RDX compositions: 50/50 and 25/75. The detonation waves were unloaded into the following materials: aluminum, plexiglas, polystyrene foam with various initial densities, precompressed argon, and argon and air at normal pressure.

The shock wave velocities were measured either oscillographically by means of electrical contacts [3] or with a moving-image camera [3, 5]. In certain cases the measurements were made on different bases in order to check the possible dependence of the wave velocity on the distance to the charge. However, in the case of relatively long charges and small bases (5–10 mm for solid targets and 10–20 mm for gases) no such dependence is observed, and within the limits of experimental error the measurements led to the same values of the wave velocities.

The experimental setup used to determine the parameters of the shock waves in compressed argon is illustrated in Fig. 1.

The sealed steel chamber 2, in which the charge 1 was placed, was filled with argon under pressure. The charge was secured in the chamber by means of a foam-plastic ring 4. The charge was initiated through the bottom of the chamber (Δ = 10 mm) by means of an auxiliary charge 3 with a plane detonation front. The process of propagation of the shock wave through the compressed argon was recorded through a plexiglas window 6 by a moving-image camera 7. The pressure in the chamber was monitored with a manometer connected to tube 5.

A simplified arrangement was used for the experiments on argon and air at atmospheric pressure. The results of the experiments on argon, air, and solid targets are presented in the table.

Material	ρ_0, g/cm³	D, km/sec	u, km/sec	p, kbars
TNT/RDX 50/50				
Aluminum*	2.71	7.43	1.565	312
Plexiglas	1.18	6.60	2.50	195
Polystyrene	0.7	5.59	3.16	123
Polystyrene	0.5	5.45	3.56	96
Polystyrene	0.3	5.39	3.90	63
Argon $p_0 = 100$	0.206	5.46	4.32	48.5
Argon $p_0 = 50$	0.095	6.03	4.80	27·5
Argon $p_0 = 25$	0.048	6.55	5.28	16.6
Argon $p_0 = 10$	0.018	6.72	5.90	7.15
Argon $p_0 = 1$	0.00186	8.96	7.61	1.25
TNT/RDX 25/75				
Aluminum**	2.71	7.72	1.765	369
Plexiglas	1.18	6.87	2.76	227
Polystyrene	0.7	5.94	3.48	146
Polystyrene	0.5	5.79	3.92	113
Polystyrene	0.3	5.76	4.20	72.5
Argon $p_0 = 100$	0.185	6.04	4.72	52.7
Argon $p_0 = 50$	0.090	6.48	5.30	30.6
Argon $p_0 = 25$	0.044	7.04	5.84	18.2
Argon $p_0 = 10$	0.0175	7.36	6.40	8.25
Argon $p_0 = 5$	0.00855	8.05	7.00	4.82
Argon $p_0 = 3$	0.00513	8.49	7.08	3.09
Argon $p_0 = 1$	0.00185	9.13	7.82	1.31
Air $p_0 = 1$	0.00129	9.25	8.04	0.96

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*From [6].

**The parameters in the aluminum target were determined in the same way as in [6] in order to determine the Jouguet parameters of the given composition.

3. In measuring the shock wave velocities in argon we used as time marks the onset of luminescence upon arrival of the detonation wave at the gas interface and the cessation (or change in intensity) of luminescence upon reflection of the shock wave from the transparent barrier (in our case plexiglas). Since plexiglas begins to lose its transparency only at pressures above a certain limit, the photographic records of expansion of the explosion products into argon at different initial pressures are different in character. The photographs in Fig. 2a–d were obtained at initial argon pressures p_0 = 1, 10, 50, and 100 atm, respectively.

An examination of the photographs and estimates of the reflection pressures indicate that up to pressures of about 30 kbars the plexiglas remains transparent. On the interval ~ 30 – 120 kbars it gradually loses transparency and at higher pressures becomes nontransparent. For comparison we note that according to the data of [7] plexiglas does not lose transparency before being destroyed by the tension wave, while according to [8] glass remains transparent up to the application of a pressure of 10^5 atm, when plastic flow commences.

The change in luminescence intensity after reflection from the plexiglas of the first wave traveling through the argon and its total cessation at the instant of arrival of wave 2–3 reflected from the explosion products (see Fig. 3, which shows the x-t diagram of the shock waves in argon; here, 024 is the explosion products-argon interface, and 135 the argon-plexiglas interface) make it possible to establish, apart from the velocity of the first shock wave (0–1), the instants of arrival of the second wave (2–3), whose front (at not very large initial gas densities almost coincides with the explosion products interface (0–2). To check the correctness of the interpretation of the photographic records we conducted additional experiments in which the thickness of the argon layer was varied.

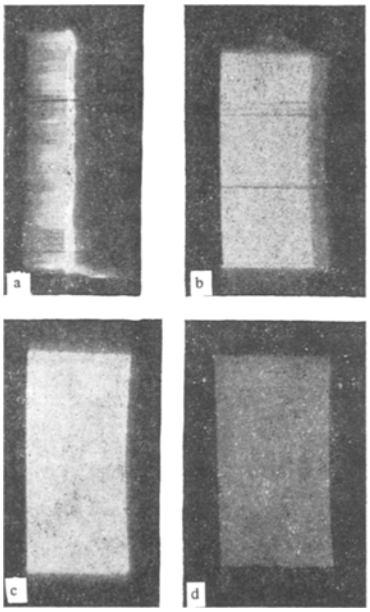

Fig. 2

The experiments confirmed that the stepwise change in luminescence intensity is associated not with any relaxation processes but with the circulation of the shock waves in the argon.

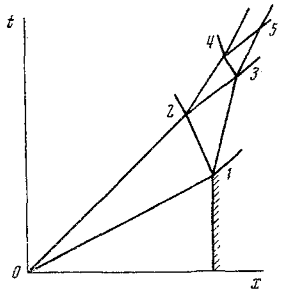

Fig. 3

From these data it is possible to establish quite accurately, without resorting to calculations, the points of intersection of the corresponding argon shock Hugoniots and the isentropes of the explosion products at pressures in the forward waves not exceeding 30 kbars.

Curves a, b, and c in Fig. 4a were calculated with allowance for single ionization of the argon at initial compression $p_0 = 10$, 25, 50 atm, respectively: points 1 and 2 are the results of experiments on the expansion of the explosion products of TNT/RDX 25/75 and 50/50, points 3 were determined from the shock wave in front of a flying plate; the data have been reduced to the same initial temperature of 10° C. Two of the curves ($p_0 = 10$ and 50 atm) were checked in control experiments in which a shock wave was created in the argon by a steel plate traveling at a known velocity (an explosive device for accelerating a steel plate to 5.6 km/sec is described in [3]).

The calculations were made on the assumption that under these conditions argon may be regarded as a perfect, singly ionizing gas, as assumed in [9]. From a comparison of the experimental points and the calculated curves it follows that in this region of densities and temperatures the assumptions are quite justified. Therefore at $p_0 = 100$ atm the points on the isentropes of the explosion products were found using the calculated Hugoniot of argon obtained on the same assumptions.

4. The solid curves in Fig. 4b represent in p-u coordinates calculations based on equation of state (4.1); the dashed lines represent the data of [5] for composition B; and the chain-dotted lines represent the data of [4]: straight lines 01 and 02 are detonation rays, points 1 and 2 the experimental results for the isentropes of the explosion products of TNT/RDX 50/50 and 25/75.

In determining the parameters of state in the plexiglas targets we used the experimental dynamic compression data from [10, 11]. It should be noted that the experimental point on the isentrope of the explosion products of TNT/RDX 25/75 lies within the region in which plexiglas undergoes phase transformation [11]. This explains the rather high level of indeterminacy in the position of the given point on the isentrope of the explosion products (Fig. 4b). For polystyrene the shock Hugoniots at three initial densities were taken from [12]. To determine the parameters of state in argon and air at normal pressure from the measured wave velocities, we used the shock Hugoniots of these gases from [13, 14] for argon and [15] for air, where the calculations were made with allowance for multiple ionization.

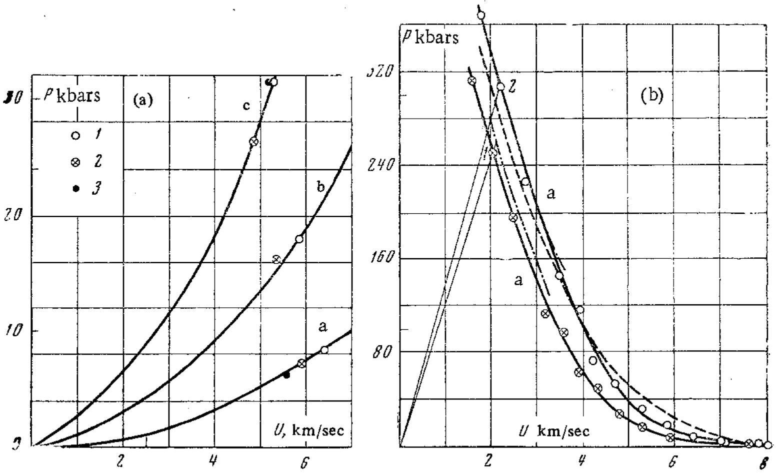

Fig. 4

Generally speaking, the upper points obtained for aluminum targets lie not on the isentropes but on the second shock adiabats of the explosion products. However, since they are not very far removed from the Jouguet points, considering the tangency condition, at these pressures, it is possible to neglect the difference in the behavior of the second shock adiabats and the isentropes.

We present values of the Jouguet parameters obtained from the points of intersection of the wave rays ($p = \rho_0 uD$) and the corresponding isentropes, together with the initial densities and detonation velocities:

Explosive	ρ_0, g/cm³	D, km/sec	u, km/sec	p, kbar	ρ_1, g/cm³
TNT/RDX 50/50	1.65	7.55	2.02	252	2.25
TNT/RDX 25/75	1.72	8.15	2.20	308	2.35

For comparison Fig. 4b presents the isentropic loading curve obtained by Deal [5] for composition B (TNT/RDX 35/65), which with respect to the component ratio is intermediate between the compositions investigated in our experiments. At relatively high pressures all three isentropes are arranged in the anticipated order, but as the pressure falls they intersect, which is very difficult to explain.

In fact, as the percentage RDX content increases both the caloricity and the content of gaseous components in the explosion products should increase monotonically, which should involve a monotonic change in the properties of the expanding explosion products with variation in the RDX percentage of the composition.

We note that as a whole Deal's experimental data are satisfactorily described if the isentrope of the explosion products is taken in the form $p = A\rho^n$. In more recent work (for example, [16]) it is noted that this form of the isentrope cannot correspond to the complete range of experimental data over a broad interval of pressures of the expanding explosion products.

The same Fig. 4b presents data obtained for the same compositions in connection with an investigation of the particle velocity distribution behind the detonation front [4]. However, we note that in [4] the explosive (TNT/RDX 50/50) had a high initial density (1.68 g/cm^3); this explains the discrepancy between the curves in Fig. 4b. The curves from [4] are slightly different: they have a somewhat smaller slope (in absolute magnitude) in comparison with the isentropic curves we obtained.

To derive the equation of state of the explosion products the data obtained may conveniently be represented in p-ρ coordinates. The isentropes passing through the Jouguet points are easily obtained in the necessary coordinates by integrating the relation

$$\frac{d\rho}{\rho^2}=\left(\frac{du}{dp}\right)_s du$$

We present the values (in kbar) of p_1 for composition TNT/RDX 50/50 and p_2 for TNT/RDX 25/75 obtained as a result of such an integration for a series of values of ρ in g/cm^3:

ρ	2.40	2.35	2.25	2.1	1.9	1.7	1.5	1.3
p_1	308	292	252*	204	143	92.0	58.5	39.1
p_2	325	308*	265	216	154	104	67.2	44.0

ρ	1.1	0.9	0.7	0.5	0.4	0.4	0.2	0.1
p_1	24.8	13.7	7.6	4.5	3.5	2.5	1.1	0.9
p_2	27.5	16.0	8.6	5.2	4.1	3.0	1.5	1.3

From these data we constructed the equations of state of the explosion products of the investigated compositions. The equation of state was written in the form:

$$p = p_x(\rho) + \gamma(\rho)\rho(E - E_x) \tag{4.1}$$

Here, p_x and E_x are the pressure and internal energy components, which depend only on the density, and $\gamma(\rho)$ is the Grüneisen constant, which gives the value of the thermal component in the equation of state of the explosion products. The function $\gamma(\rho)$ was determined from the data, starting from which the detonation characteristics were calculated in [17]. It proved possible in a good approximation to represent $\gamma(\rho)$ for both the investigated compositions by a single expression:

$$\gamma=\gamma_0+\frac{l}{\rho}e^{-k/\rho} \tag{4.2}$$

with the same values of the constants $\gamma_0 = 1/3$, $l = 7.425$ g/cm^3, and $k = 4.95$ g/cm^3. The selected form of the $\gamma(\rho)$ relation ensures the reduction of γ to a value approximately corresponding to a perfect gas as the density of the explosion products decreases and also a weak decrease in γ upon compression of the explosion products in the high-density region from a maximum value $\gamma \approx 0.7$.

The $E_x(\rho)$ relation was taken in the form

$$E_x = ae^{-k/\rho} - b\rho^m + A[(\rho-\rho_1)^3 + B]e^{-\alpha(\rho-\rho_1)^2} \tag{4.3}$$

where ρ_1 is the density at the Jouguet point, which is different for the compositions investigated, while the values of the remaining constants are the same:

$$a = 234.66\cdot10^{10},\quad A = -0.48557\cdot10^{10},\quad R = 11.25$$
$$b = 0.042077\cdot10^{10},\quad B = -1.5574\cdot10^{10},\quad m = 2,\ \alpha = 2.1051$$

The equation of state obtained satisfactorily describes the experimental data on the isentropic expansion of the explosion products. The isentropes are obtained from

$$\left(\frac{\partial E}{\partial\rho}\right)_s=\frac{p}{\rho^2}$$

after differentiation of (4.1) and subsequent integration; the constants of integration are determined from the parameters of the Jouguet point.

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*Jouguet points.

Apart from conforming with the experimental points on the isentropes, the parameters of the equation of state were also required to conform with the experimental heats of explosion and the experimentally determined slope of the velocity drop at the normal detonation front [4]. Basically, the latter condition also required the introduction into the equation of state of a complicating exponential term, which reduces the curvature of the isentrope near the Jouguet point.

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